ELECTRIC POWER RESEARCH INSTITUTE

Potential Failure Mode Analysis for Coal Combustion Residual Impoundments

Guidance Document

2015 TECHNICAL REPORT

Potential Failure Mode Analysis for Coal Combustion Residual Impoundments

Guidance Document

3002006289

Final Report, October 2015

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NOTE

ACKNOWLEDGMENTS

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This report describes research sponsored by EPRI.

EPRI and the authors also want to thank Nick McClung and the Tennessee Valley Authority for their support and assistance throughout this project.

This publication is a corporate document that should be cited in the literature in the following manner:

Potential Failure Mode Analysis for Coal Combustion Residual Impoundments: Guidance Document. EPRI, Palo Alto, CA: 2015. 3002006289.

ABSTRACT

Potential Failure Mode Analysis (PFMA) is required by Federal Energy Regulatory Commission (FERC) regulations for hydropower dams but is not required for coal combustion residual (CCR) impoundments. This EPRI report provides guidance, adapted from the FERC guidelines, for utilities that want to voluntarily conduct a PFMA at their CCR impoundments. The product of the PFMA exercise is not a decision document or an audit of the quality of the design or operations, but rather an informational resource document, developed from the combined input of the PFMA team, that is intended for use and reference for many years.

The report presents guidance and supporting material to enable a PFMA to be carried out for CCR impoundments. Covered topics include the following:

- A brief overview of the PFMA including general principles, key goals, objectives, and anticipated outcomes
- A guide to assembling the PFMA core team, including roles and responsibilities
- Step-by-step instructions for conducting and documenting the PFMA exercise, including potential failure mode considerations unique to CCR ash impoundments
- Guidelines for conducting a more streamlined version of the PFMA (Rapid PFMA)

Keywords
Coal ash
Coal combustion residuals
Impoundments
Potential Failure Mode Analysis
Risk

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INTRODUCTION

The guidelines presented in this document provide recommendations for performing a Potential Failure Mode Analysis (PFMA) for coal combustion residual (CCR) storage facilities. These guidelines were adapted from procedures developed originally for the dam safety industry – first by the U.S. Department of Interior Bureau of Reclamation and the U.S. Army Corps of Engineers, and then expanded by the Federal Energy Regulatory Commission (FERC) for hydropower dams.

PFMAs are required by FERC regulations for hydropower dams, but are not required for CCR impoundments. This document provides guidance adapted from the FERC guidelines for those utilities that want to voluntarily conduct a PFMA. The product of the PFMA exercise is not a decision document or an audit of the quality of the design or operations, but rather an informational resource document, developed from the combined input of the PFMA team, that is intended for use and reference for many years.

The intent of the PFMA is to help reduce the risk posed by the storage facility by 1) improving and focusing the project's safety monitoring procedures, 2) suggesting risk reduction measures to improve safety, and 3) providing improvements to the safety inspection process by focusing on the site-specific factors that are of greatest importance. Traditional safety evaluations have focused on a limited number of standards-based concerns, such as hydraulic capacity of spillways or stability of structures under a predefined set of loading conditions. PFMAs are intended to broaden the scope of safety evaluations to include potential failure scenarios that may have previously been overlooked, including operational and maintenance issues. By definition, the PFMA is an exercise to identify all potential failure modes that may result in an uncontrolled release of contents or breach under static, normal operating water level, rapid drawdown conditions, flood conditions, earthquake loading, and all other plausible loading cases the storage facility may experience during its service life. Potential failure modes can also be triggered by operational factors such as failure of pond level instrumentation, gates, valves, or sluice pipes, or mis-operation of facilities such as overpumping of settling ponds or overdredging of ash ponds at the toe of containment dikes.

With the high-profile failure of several hydraulically placed ash landfills since 2008, the PFMA process has been successfully used at a few above-ground CCR impoundments (perimeter embankment or retention dam) to better understand the existing and future risks related to storage of CCRs at a given impoundment facility. The fundamental difference in the PFMA process between CCR impoundments and water-retaining dams is that dams are generally built to their final size and geometry before being put into service. The life cycle of CCR impoundments begins with initial filling and, in the case of perimeter embankment designs, this is often followed by increase in height and volume as the containment dikes are raised to accommodate additional fill. The staged build-out plan, rate of sediment placement, type and location of sediment discharge, geometry, operation, and a number of other factors can all change during the period of active filling prior to final closure and capping. After closure, the risk of failure is still present but can gradually diminish over time as phreatic levels within the ponded CCRs fall. The history of filling to date, design features, future filling plans, and ultimate closure and long-term monitoring plans must all be considered since the PFMA process must account not only for the current potential failure modes but how existing ones are expected to change with time and the potential for new ones to develop later in the CCR impoundment's life cycle. The PFMA exercise not only provides value in highlighting failure modes that pose the greatest risk to the structure currently, but also highlights data gaps where additional information may be needed to assess the risk of a given loading to the impoundment. Modifications, including focused instrumentation and monitoring, can then be incorporated into the designs, filling plan, or closure plan to improve the overall safety of the structure.

This document provides guidance and supporting material to enable a Potential Failure Mode Analysis to be carried out for CCR impoundments, including:

- A brief overview of the PFMA including general principles, key goals, objectives, and anticipated outcomes;
- A guide to assembling the PFMA Core Team, including roles and responsibilities;
- Step-by-step instructions for conducting and documenting the PFMA exercise, including potential failure mode considerations unique to CCR ash impoundments;
- Guidelines for conducting a more streamlined version of the PFMA (Rapid PFMA); and
- Appendices containing supporting materials and examples from a PFMA.

The guidance provided in this document is largely based on Chapter 14 – *Monitoring the Performance of Dams* of the FERC's Engineering Guidelines for the Evaluation of Hydropower Projects and Chapter 2 – *Potential Failure Mode Analysis* of the Bureau of Reclamation's Best Practices and Risk Methodology, along with lessons learned and shared by FERC dam safety staff in various forums since the PFMA process was incorporated into the Part 12D Inspection process for hydropower dams in 2003.

2
PFMA OVERVIEW

A Potential Failure Mode Analysis is an informal examination of "potential" failure modes by a team of persons who are qualified either by experience or education to evaluate each impounding structure. An adequate job of identifying potential failure modes can only be performed after all participants in the PFMA exercise have thoroughly read all relevant background information on the structure, including geology, design, analysis, construction, operations, relevant loadings (e.g., floods or earthquakes), safety evaluations, and performance monitoring documentation. Photographs, particularly those taken during various stages of construction or unusual loading events, are often key to identifying issues related to potential failure modes. It is essential that the records be diligently collected prior to the meeting, cataloged, and reviewed during the meeting, even if those involved are already familiar with the facility.

All PFMA participants should also take part in a site examination. The PFMA team should look for clues as to how the impoundment facilities might be vulnerable to an uncontrolled release or breach. Operations personnel should be involved in the examination and questioned as to how the impoundments have been operated, filling rates, discharge locations, construction of the containment dikes, future expansion, and history of past incidents and how they were handled. They should also be asked their opinion as to where the vulnerabilities for failure may lie that could lead to a breach.

The PFMA process is not an audit or a forum to criticize the Owner, operator, or design. It is meant to increase the level of knowledge of how the facility was chosen, designed, constructed, and operated. The interaction of a diverse team of stakeholders and individuals from many disciplines who have information on operation and performance often reveals vulnerabilities that would otherwise be missed. Using an intensive team inquiry process, beginning from a basis of no preconceived notions, the potential failure mode examination process has the ability to:

- Enhance the safety inspection process by helping to focus on the most critical areas of concern unique to the impoundment under consideration;
- Identify operational-related potential failure modes;
- Identify structural-related potential failure modes (e.g., seepage break-outs, internal erosion, and piping) not covered by the commonly used analytical methods (e.g., global slope stability);
- Enhance and focus the visual surveillance and/or instrumented monitoring program;
- Identify shortcomings or oversights in data, information, or analyses necessary to evaluate impoundment safety and each potential failure mode;
- Help identify the most effective impoundment safety risk reduction measures; and

- Document the results of the PFMA study for guidance on future safety inspections. By periodically revising and updating the PFMA report, the benefit of increased understanding of the failure modes that most impact the overall safety of the CCR impoundment remain highlighted and the insight provided by the process is passed on to the Owner's operations and engineering staff and Owner's consultants involved in future inspections.

2.1 Key Goals, Objectives, and Typical Outcomes

The primary outcome and the main focus of a Potential Failure Mode Analysis is identifying and obtaining a clear understanding of each impounding facility's site-specific potential failure modes. At the outset of the PFMA, the independent Facilitator should discuss with the entire team that the product of the exercise is not a decision document but rather an informational resource document, developed from the combined input of the team, which is intended for use and reference for many years.

The potential failure mode "identification" is intended to go beyond a simple generic statement of the potential problem (e.g., piping, slope instability, dike overtopping, etc.). The potential failure mode identification, examination, and description provide information on:

- Loadings and/or structural or operational conditions present that initiate or trigger the failure process.
- The step-by-step mechanisms that must occur to lead to a breach and uncontrolled release of stored contents.
- The expected magnitude and consequences of a breach.
- The factors present that make a particular failure more or less likely.
- An assessment of whether a particular failure mode presents relatively greater or lesser risk to the facility. The most significant potential failure modes and failure scenarios will be identified and documented for use and consideration by future inspection teams. Certain problems, issues, and concerns that have been associated with an impoundment may be found to be of lesser significance than previously perceived from the standpoint of consequence, remoteness, or physical possibility.
- Gaps in data, information, or analyses that prevent characterizing the significance of a potential failure mode and are recognized and identified for consideration/action by the Owner.
- Recommendations regarding the following: the need for failure mode awareness; enhancements to the inspection, monitoring and surveillance program; emergency preparedness; operational changes; or structural repairs or modifications that can mitigate the risk for failure mode development and/or failure consequences.

In addition, the process of searching out all the information about the CCR impoundment for the specific purpose of identifying potential failure modes (plus the involvement of a diverse group of people in the PFMA process) typically results in uncovering data and information that most personnel currently involved in the facility's safety evaluation had not been aware of. This provides the opportunity to easily and effectively educate all who are concerned with the facility (Owner, regulators, operators, independent inspectors, designers, and others) about:

1. The potential failure modes for this structure;
2. How monitoring, including use of specific instrumentation and visual surveillance, is used to look for specific symptoms, behaviors, or evidence that might warn of a developing failure for the identified potential failure modes;
3. How "general health" monitoring (e.g., piezometers, inclinometers, settlement monuments, and weirs) is used as basic data to help watch for conditions that were not identified as potential failure modes;
4. How operations at the facility may influence safety; and
5. Emergency actions that may be more commonly encountered.

2.2 General Principles of the PFMA Process

It is very important that the principles of the process be understood and followed in order for the full value of the process to be achieved. These principles include:

- Diligence in searching for all the available background information;
- An open, investigative attitude toward identifying and understanding potential failure modes and failure scenarios;
- Dedication of the assigned persons to the reviewing/reading of all the background information on the CCR impoundment prior to the PFMA session;
- Diversity in input to the process – field personnel, operations personnel, technical personnel, management personnel, and others all contribute to the pool of information. There is no monopoly on good ideas and key information;
- Documentation as the key to capturing the insight and ideas resulting from the process; and
- Willingness of all parties to set aside their normal hats and focus on what the data, information, and experience/knowledge of individuals can teach the participants about the storage facility.

2.3 Core Team Roles and Responsibilities

The Potential Failure Mode Analysis participants (team members) consist of all those who will participate in the brainstorming session during which potential failure modes are identified, defined, discussed, and categorized. Fundamentally these are persons who have past experience with the design, construction, analyses, performance, and operation of the CCR impoundment or who will obtain knowledge of the project through reading all the background material. An engineering geologist, or a geotechnical engineer experienced with dams or CCR impoundments, should be a part of the team and should be included in the site visit. The primary advantage of having a variety of people participate in the potential failure mode identification process is that more ideas and more questions are put forward; more knowledge and information is available; and a greater diversity of opinion is input to the process.

Some of the team members have specific roles and responsibilities and need to have the requisite experience and capability to fulfill these roles. The roles and requirements of the team members are given in the following sections.

2.3.1 Team Leader

The facility Owner should designate one person to function as the Core Team Leader, responsible for coordination activities including collection of the background information, arrangements for the site visit and attendance by operating personnel, and organizing the PFMA session including meeting place, materials (e.g., projector, large tables, reference material, large flip charts, colored markers, etc.).

2.3.2 Core Team

The PFMA session "Core Team" members should be a minimum of 4-6 individuals who are specifically responsible for reading and reviewing all the background material, and who, once a potential failure mode has been fully described and developed, determine the appropriate risk categorization for the failure mode based on the information available. Core teams generally do not have more than about 10-12 people.

The Core Team will generally consist (as a minimum) of the following persons:

- The Independent Engineering Consultant(s) (IC) who will serve as lead author in preparing the Potential Failure Mode Analysis Report.
- Technical Representative(s) of the Owner's staff (i.e., engineer, field operations person). One of these individuals may or may not function as the Team Leader (see note below).
- The Facilitator of the Potential Failure Mode Analysis session who is independent of the original designer and Owner and who will facilitate the session and peer-review the Potential Failure Mode Analysis Report on behalf of the Owner and all the participants. This individual should have at least 20 years of experience in dam safety and/or CCR impoundment engineering and good meeting leadership and communication skills.
- It is strongly recommended that an engineering geologist and/or a geotechnical engineer be included in the Core Team. Experience has shown that this expertise has proven valuable during the PFMA sessions, and the people filling these roles should have the benefit of reading the background material.

Note: The Team Leader may or may not be assigned by the Owner as one of the designated Core Team "readers of the material." This is because the coordination/logistic activities may keep the Team Leader from being able to meet the reading and review requirements. If the Owner and Team Leader consider that this may be the case, another representative of the Owner should be designated to participate in the Core Team review of all the available background material.

The following criteria should be considered when selecting the Core Team members:

General Criteria

- The Core Team members should have knowledge and experience related to CCR operations and impoundment safety evaluations. It is especially helpful to have persons who have interest and knowledge related to CCR impoundment failures and who have an inquisitive/investigative personality.
- The Facilitator should, in general, be new with respect to examining the CCR impoundment's operation and history. This is considered an advantageous situation with

respect to providing a fresh and vigorous look at the structure. It is generally considered inappropriate for Owners to facilitate the PFMA on their own structures.

- Typically, the Independent Engineering Consultant is not part of the Owner's staff but is an independent engineer with extensive experience in dam and/or CCR impoundment engineering and safety issues inherent in these types of structures. The IC may or may not be familiar with the facility. The IC and the Facilitator should not be the same person or from the same organization.
- Key operations personnel and/or site personnel with responsibility and for knowledge of day-to-day operations and project history.
- Persons who had experience with the original design and/or construction of the project can provide invaluable insights and data. Wherever possible, they should be recruited for the PFMA field and data review and the PFMA session. Alternatively, they can be available by phone to answer questions raised during the session.

2.3.3 Facilitator Requirements

The PFMA Facilitator should be a civil or geotechnical engineer, or an engineering geologist with a broad background and experience in dam safety or CCR impoundment engineering and experience in performing a PFMA similar to that described in this guidance. A recommended qualification for the Facilitator is that they should have been involved in an actual PFMA of the nature described in these guidelines either as a Core Team member of a PFMA or by actually facilitating a PFMA. This ensures that the person leading the PFMA process not only knows how the process is carried out, but is also aware of what can be accomplished. This is especially critical if the other Core Team members have not been through a PFMA, which may often be the case. There are many experienced engineers approved by the U.S. Bureau of Reclamation and the Federal Energy Regulatory Commission (FERC) who are approved as ICs and Facilitators for dams and who have demonstrated expertise with performing PFMAs, and many of them also have CCR impoundment experience.

2.3.4 Additional PFMA Participants

In addition to the Core Team members, the PFMA session should include the key operating staff that will be able to clarify operating rules and procedures and also will learn about the failure modes developed in the process. Also, if not a designated Core Team member, an individual with a background in engineering geology who is experienced with dams or CCR impoundment structures should participate in the PFMA and should review all geological background material, make appropriate observations during the field review, and participate in discussions of foundation-related PFMs.

In formulating the team it is important to include those individuals with intimate knowledge of the project operations and structures, especially the senior engineering and operations staff responsible for collecting and interpreting monitoring data. The benefits from conducting this exercise not only include bringing focus to the most likely modes of failure based on engineering judgment but also include increasing the general awareness of structure safety issues by sharing knowledge at all levels. Experience has shown that it is very helpful and valuable to include senior (experienced) field operating personnel in the actual PFMA session because all information has not been written down and in certain cases assumptions in written reports differ from what is actually done or known in practice (institutional knowledge). The field personnel also can verify data and information discussed in the session.

2.3.5 Supplemental Resources

In addition to the team participants there are other people who have specific technical knowledge or experience that may be useful to the team. These people would be notified and asked to be available or on call on the day of the PFMA session. This would include such persons as those involved with the construction of the facility, seismo-tectonic specialists, hydrologists, structural engineers, civil engineers, environmental engineers, mechanical engineers, geotechnical engineers, field personnel, scientists, inspectors, instrumentation personnel, emergency preparedness personnel, etc. If there has been a major change to the project or if there is a complex instrumentation program (unique instrument), it is useful to have the responsible engineer/operator make a short presentation during the workshop so that all participants have a common understanding of the issue.

2.4 Overview of Steps in the PFMA Process

The “conventional” PFMA process, long used in the dam safety community by organizations such as the U.S. Bureau of Reclamation, the U.S. Army Corps of Engineers, and the FERC, involves the following basic steps:

- Step 1 Assemble the PFMA Core Team.
- Step 2 Collect background data on the CCR Facility for review by the Core Team.
- Step 3 Perform the site review including interviews with key Owner personnel at the Facility.
- Step 4 Perform a comprehensive review of all of the background data on the Facility by the Core Team.
- Step 5 Conduct the PFMA session.
- Step 6 Prepare the PFMA report for Core Team review.

These steps in the PFMA process are described in greater detail in Section 3. Steps 3, 4, and 5 when the entire PFMA Core Team is assembled generally take anywhere from 3 to 5 days to complete, depending upon the size and complexity of the facility, number of participants, amount of background data to review, and number of potential failure modes generated.

More recently, FERC has allowed a more streamlined “rapid” process for supplemental Potential Failure Mode Analysis associated with major repair or dam reconstruction projects. This same process has been found to be valuable for initial PFMAs at CCR impoundments. The basic steps in the Rapid PFMA are essentially the same as in the conventional PFMA – the main difference is that the Independent Consultant evaluates the background information and prepares a draft of the PFMA report in advance of the PFMA session. The IC then presents each of the failure modes at the PFMA session, and the Core Team reviews and discusses each of the developed failure modes and either agrees with or proposes modifications to the list. One of the big benefits of the Rapid PFMA approach is that the Core Team can evaluate a facility within 1 day, compared to 3 to 5 days using the conventional approach. A major disadvantage to the Rapid PFMA process is that the Core Team may not have the same level of engagement in the PFMA process as compared to the conventional process, and may not develop the same level of understanding of all the issues and contributing factors without reviewing all the background data. For this reason, it is important that for the Rapid PFMA approach to be successful:

1. The selected IC who will prepare the PFMA report for review by the Core Team should be already be familiar with the facility.
2. The IC should be open to differing opinions and discussions that take place during the PFMA session.
3. The Core Team members must review the PFMA report in advance of the PFMA session and be ready to provide their input and knowledge into the PFMA discussions. Active participation is key.

The Rapid PFMA process is described in greater detail in Section 4.

3
CONDUCTING THE PFMA

3.1 Step 1 – Assemble the Core Team

The Potential Failure Mode Analysis participants (Core Team members) consist of those individuals who will participate in the brainstorming session in which potential failure modes are identified, defined, discussed, and categorized. Fundamentally, these are persons who have past experience with the design, construction, analyses, performance, and operation of the CCR impoundment or who will obtain knowledge of the project through reading all the background material. The primary advantage of having a variety of people participate in the potential failure mode identification process is that more ideas and more questions are put forward; more knowledge and information is available; and a greater diversity of opinion is input to the process.

3.2 Step 2 – Collect Background Information for Review by the Core Team

All available background information on the project is to be collected in a centralized location for reading by the Core Team members and would also need to be available during the PFMA session. The general rule of thumb is to collect all information on the project. If there is a question about the need to bring/collect certain material, the Facilitator and Owner should discuss this in advance. The types of material that should be collected (if available) include the following:

- Construction record reports including historical photos from original construction to date.
- Available design information including:
  - Foundation condition reports.
  - Geotechnical data reports with detailed site characterization information on the foundations.
  - Designation of areas where wet sluicing versus dry stacking has occurred.
  - Geographic and topographic setting.
  - Staged filling and rate of loading information.
  - Impoundment construction method (upstream, centerline, or downstream dike containment).
  - Information on internal drains and filters.
  - Material types (engineered fills, bottom ash, fly ash, gypsum, etc.) and engineering properties of all representative material comprising the foundation, containment dikes, and impounded CCR material (e.g., erodibility, grain size analyses, static and cyclic strength, hydraulic conductivity, etc.).

  - Locations of dike pipe penetrations and conduits (do we know where they all are? inventory available? type and condition?).

- Current or most recent CCR impoundment safety engineering analyses, including stability and stress analyses.
- Annual and periodic inspection reports by Owner, regulators, and independent consultants.
- Current hydrologic studies and hydraulic information on the existing outlet works and spillways.
- Available stormwater management plans.
- Vertical and/or horizontal expansion plans.
- Closure and post-closure plans.
- Most-recent and historical monitoring and instrumentation data, including time history plots for piezometers, slope inclinometers, movement and settlement monitoring, staff gauges or other pond level sensors, seepage monitoring weirs, weirs of flowmeters at spillways, etc.
- Verification that the instrumentation is functioning properly.
- Information on the Owner's Impoundment Safety Inspection Program, including information on:
  - What is currently in place?
  - Who has responsibility for review of the instrumentation and monitoring data?
  - Frequency of data review?
  - Procedures for addressing spurious data?
  - Inspections performed by third-party inspectors, regulators, Owner?
- The current Emergency Action Plan.
- Operation and maintenance documents.
- The most up-to-date aerial photographs of the downstream areas that could potentially be impacted by failure of the project structures.
- Original and subsequent modification construction design reports, as-built drawings, and photographs.
- The most recent seismic loading parameters that have been prepared for the site and records of recent seismic activity.
- Any incident reports.

A listing of the data available for review and considered in the Potential Failure Mode Analysis should be prepared for use by the Core Team in reviewing the materials and should be included in the PFMA report documentation. The Owner should establish a means to retain/archive all the information collected for the PFMA.

An advance review package on the CCR impoundment is often valuable – particularly for the Facilitator and members of the Core Team who are not familiar with the project site. The advance review package should be sent or provided electronically to site review participants prior to their travel to the site.

Core Team members are to review all of the above information searching for site-specific conditions or situations that would lead to uncontrolled release of the reservoir or other incidents, conditions, or situations that would have an adverse impact. This review of materials is scheduled to occur following the site visit and discussion with project personnel (see Step 4 below).

3.3 Step 3 – Conduct the Site Tour and Interviews

Typically the PFMA team (the Core Team and the Owner's personnel) is first assembled at the time of the site review. This is a good occasion for the Facilitator to review the basic concept of the PFMA process and the objectives of the site review and ask if there are any questions. Likewise, when the Core Team gathers to do the reading of the background information, a quick discussion of the plan and objectives of the reading by the Facilitator is appropriate.

1. Prior to the initial PFMA session, a review of the site, "thinking" potential failure modes, is carried out with the Owner's personnel and the Core Team. The basic purposes of this site review are: 1) to let those participating on the PFMA team, who have not seen the site, see it; 2) to have the team "think/see" or visualize potential failure modes in the field; and 3) to discuss the site and operations with site personnel in their own environment. Owners may find it valuable to include all or most of the employees that they plan to have participate in the PFMA also participate in the project review.
2. Typically, the site walkover performed in association with the Potential Failure Mode Analysis should be scheduled just before the Core Team members review the background materials. Such a schedule takes greatest advantage of the interaction between Potential Failure Mode Analysis and site visitation. Depending on the size of the facility, the site walkover may take from a couple of hours to a day to complete. The team should view the entire CCR facility, including slopes and toes of dikes, drainage features, spillways, discharge pipes, areas of seepage, remediated areas (such as buttresses), instrumentation, etc. A review of areas potentially impacted by release should be conducted (a review of aerial photographs may be sufficient).
3. The site review should include the opportunity to discuss the facility with field maintenance personnel and impoundment operators, including but not limited to those who will be team participants.
4. The comprehensive review of background data and information on the CCR impoundment by the Core Team is scheduled to occur following the above site visit and discussion with project personnel. Experience has shown that it is much more efficient and effective to review the bulk of the background materials after a physical review of the site.

3.4 Step 4 – Background Data Review

Prior to the Core Team beginning its review of the background material, the Facilitator should review the basic concept of the PFMA process and the objectives of the material review and ask if there are any questions. The Core Team then gathers to review the compiled background information on the CCR impoundment. The review of the material should take place at a convenient off-site location considering the location of the site, data, and where the PFMA session will take place. The background material should preferably be in the same room as the PFMA session to facilitate finding reference material during the PFMA session. The off-site location allows for the PFMA session to be completed with fewer distractions.

Participants assemble in a group setting for efficiency in sharing the collected data and to provide a "captive" condition to ensure that the material is reviewed by all the Core Team members. Also, being together allows for collaboration on items that may need clarification by the entire core group.

Note: Depending upon the amount of background information available, one full day plus one half-day during the day of the site tour is generally budgeted for the Core Team to complete the Data Review. However, the review may take even longer if needed for all of the Core Team members to thoroughly review the background information. This review is essential to an effective PFMA and should not be rushed.

3.5 Step 5 – Conduct and Document the PFMA Session

A brief description of the PFMA session is given below. It is important for the Facilitator to involve all participants in the discussions and give everyone an opportunity to provide their knowledge, understanding, and views on the potential failure modes, consequences, and possible risk reduction actions/measures. An example outline for a typical PFMA session from Chapter 14 of the FERC Guidelines for hydropower dams is attached in Appendix A. The process is similar to that used for CCR impoundments.

As discussed for the site review and the reading session, the Facilitator should give some introductory remarks about the PFMA session (e.g., goals, objectives, process) and provide everyone a handout on the PFM category descriptions (see Table 3-1 below) at the outset of the PFMA session. The Facilitator should also explain that the product of the exercise is not a decision document or an audit of the quality of the design or operations, but rather an informational resource document, developed from the combined input of the team, that is intended for use and reference for many years.

Table 3-1
Potential Failure Mode Categories

Category	Description
I	Highlighted Potential Failure Modes – The potential failure modes of greatest significance are highlighted, considering need for awareness, potential for occurrence, magnitude of consequences, and likelihood of adverse response (physical possibility is evident, fundamental flaw or weakness is identified, and conditions and events leading to failure seem reasonable and credible).
II	Potential Failure Modes Considered but Not Highlighted – These are judged to be of lesser significance and likelihood. Note that even though these potential failure modes are considered less significant than Category I, they are all also described and included, with reasons for and against the occurrence of the potential failure mode. The reason for the lesser significance is noted and summarized in the documentation report or notes.
III	More Information or Analyses Are Needed in Order to Classify – These potential failure modes to some degree lacked information to allow a confident judgment of significance, and thus a safety investigative action or analysis can be recommended. Because action is required before resolution, the need for this action may also be highlighted.
IV	Potential Failure Mode Ruled Out – Potential failure modes may be ruled out because the physical possibility does not exist, information came to light which eliminated the concern that had generated the development of the potential failure mode, or the potential failure mode is clearly so remote as to be non-credible or not reasonable to postulate. Potential failure modes discussed that were not developed in detail were classified as Category IV-ND (not developed), generally because the PFMA team judged them to be too improbable to warrant an in-depth evaluation of adverse versus positive factors.

5a. Consider the Structures to Be Evaluated and the Relevant Loadings

Consider the possibilities for failure for each impounding structure for each applicable loading condition. The types of structures generally considered include CCR ponds/impoundments, stilling ponds, and dry stacks constructed over formerly sluiced CCRs. The loading conditions include normal operations, flood loading, seismic loading, loading due to maintenance, operation or mis-operation, and any other loading relevant to the facility. Consider how an uncontrolled release of the impoundment could occur in response to that loading. Also consider total system operation aspects (communication and response, available operations personnel on site at any time, ability to detect failure if it occurs, potential rate of failure once initiated, site access, available materials or equipment) with respect to the possibility of their contribution to development of a potential failure mode/failure scenario.

Having a set of full-sized drawings of each of the CCR impounding structures showing plan and typical section views, locations of water control features (e.g., spillways, outlet pipes, etc.), flow directions, penetrating conduit locations, and other relevant features greatly helps the PFMA process. Having the ability to readily access project digital images of the various project drawings, historical photos, and relevant background information and project them up on a wall or screen is also very useful (see example in Figure 3-1).

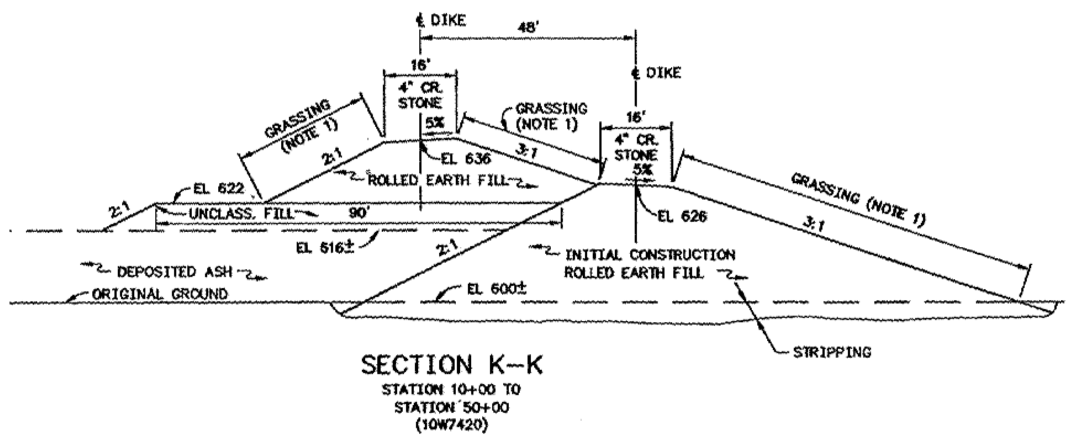

Figure 3-1
Sample Embankment Section

5b. For Each Impounding Structure, "Brainstorm" Candidate Potential Failure Modes, Loading by Loading

The Facilitator asks participants to suggest or propose "candidate" potential failure modes that they have considered during the site visit or during review of the background material. A potential failure mode (PFM) is defined as a specific chain of events that, if left unchecked, could lead to a failure of the one or more impounding structures and an uncontrolled release of stored process water or stored CCR contents. Failure does not necessarily have to be a complete and catastrophic failure of an impounding structure. Failure can be defined as water or stored CCR contents leaving the Owner's site, causing physical harm to the public or environmental damage. The Owner may also want to consider potential impacts to workers on site.

Various issues related to potential failure modes for CCR ash impoundments have been identified based on evaluation of past failures and are listed below. This list should not be considered all-inclusive as each facility must be evaluated on a case-by-case basis. However, these considerations are intended to provide "food for thought" in the development and assessment of viable potential failure modes.

Failure modes related to static slope stability:

- Deep-seated failure through weak foundation soils.
- Deep failure through containment dikes.
- Shallow sloughing of perimeter containment dikes intercepts the phreatic surface and leads to progressive slope failure.
- Domino-type (progressive) failure – failure of interior dikes, which leads to failure of perimeter containment dikes.
- High rainfall and water infiltration leads to elevated phreatic surface and containment dike instability.
- High rainfall event exceeds decant or spillway outlet capacity and leads to overtopping of impoundments and perimeter containment dike system.

- Rapid raising of ash pond faster than pore pressures can dissipate leads to undrained conditions within the containment dike soils and ash at bottom of pond and decreased slope stability.
- Blockages in ditches near perimeter dikes and continued sluicing lead to ditch overtopping and failure of containment dike.

Failure modes related to static liquefaction:

- Static liquefaction of loose, saturated ash triggered by creep movements or movement within weak foundation soils.
- Rapid loading due to an excessive rate of fill placement faster than internal pore pressures can dissipate in recently sluiced ash triggers static liquefaction of loose, saturated ash. This has occurred when divider dikes are constructed over recently placed, sluiced, wet, loose ash.
- Excessive dredging next to the toe or into the embankment of stacked or sluiced ash, as occurred at the TVA Kingston ash collection cell in August 1984.

Failure modes related to earthquake shaking:

- Earthquake-induced liquefaction of saturated, loose ash leads to containment dike failure.
- Lateral spreading or strain softening of saturated, loose ash leads to excessive movements and slope instability, causing dike failure.
- Earthquake-induced liquefaction of loose sandy foundation soils leads to global stability failure of containment dike.

Failure modes related to seepage-induced internal erosion or piping:

- Seepage-induced piping of soil around the exterior of active or abandoned pipes located within containment dikes below the phreatic surface (water table).
- Piping of embankment soil into outlet pipes due to joint separation.
- Failure/clogging of internal drainage system leads to rising phreatic levels within CCR stack, piping of embankment soils, perimeter dike failure, and loss of containment.
- Breakage or separation of pressurized sluice pipes.
- Lack of filters and drains within the embankments to control the phreatic surface and internal seepage gradients.
- Seepage breakouts on the downstream slope of containment dikes, with no filters or drains at the seepage exit points to prevent internal erosion and piping.
- Uncontrolled seepage through pervious foundation layers below the containment dikes, which leads to high exit gradients and piping under the embankment.

Overtopping-related failure modes:

- Extreme rainfall events that exceed the outlet works capacity and result in perimeter dike overtopping.

- Failure of an internal dike into a pond, triggering a wave (seiche) in the pond that overtops a containment dike across the pond from the failure location.

Operational-related failure modes or human error:

- Overdredging along toe of perimeter dike slopes resulting in slope failure.
- Stacking of dredged material from ditches or ponds faster than pore pressures can dissipate adjacent to containment dikes.
- Blockage of outlet weirs leads to overtopping of perimeter dikes during a flood.
- Unintended filling of an emergency spillway.
- Failure of gate or stop log mechanisms leads to overtopping of perimeter dikes during normal operations or a flood.
- Faulty piezometers, no inclinometer data, or inaccurate instrumentation readings that fail to identify a developing stability problem such as "creep" slides in a normally consolidated clay foundation that is being final graded and capped.

Potential failure modes related to acts of terrorism are typically not considered. However, the PFMA process may be applicable in assisting an Owner in evaluating the vulnerability and risk associated with acts of terrorism or mischievous trespass.

Each of the potential failure modes suggested should be discussed until a clear characterization of the failure mode is developed. Any potential failure modes that, by consensus, are judged to be clearly not credible or are physically not possible are set aside. These failure modes and the reasons they were ruled out will be documented in the PFMA report, but will not be developed further.

The following are carried over to the "discovery" phase to be further developed and examined: all other potential failure modes deemed credible, failure modes where there was not a clear consensus, and failure modes deemed not credible but believed by either the Owner, regulator, or one of the other members of the Core Team to warrant further discussion. Sometimes this preliminary or developmental discussion of the initial suggestion may lead to breaking one PFM into two or more separate or related PFMs, which are then developed separately.

Sometimes an item or issue is raised during the brainstorming process that relates to CCR impoundment safety, surveillance and monitoring, or design or construction, or is of general concern but is recognized by all as something that does not necessarily result in failure and is therefore not a candidate potential failure mode. Such items should still be documented and included in the PFMA report under "Additional Monitoring or Performance Related Items Discussed."

The Facilitator should then move to full consideration of each potential failure mode (sub-steps 5c - 5e) if there is no clear consensus among the PFMA team on the candidate mode's lack of credibility.

5c. Describe the Potential Failure Mode

The Facilitator should move the Team to fully develop each of the candidate PFMs. The first step is to develop a full and complete description of the potential failure sequence from initiation through failure and uncontrolled release.

There are three parts to the failure mode description:

1. **The Initiator.** This is the loading condition that triggers the failure mechanism. For example, this could include earthquake shaking, rapid stacking of fills, breakage of a sluice pipe penetrating through a containment dike, a period of heavy rainfall, foundation layer creep, etc.
2. **Failure Continuation/Progression.** This includes the step-by-step mechanisms that lead to the breach or uncontrolled release. These mechanisms have to occur in sequence for the PFM to continue or progress. The location or path where the failure is most likely to occur should also be described. For example, this might include a particular weak layer within the foundation where a failure plane could result in a sliding failure. In the case of seepage-induced piping, this would include a description of the initial point of soil movement out of the retaining dike or its foundation, the path through which materials would be transported as piping progresses, and the point where breaching and uncontrolled release of liquids or contents ultimately occurs.

   For example, a typical failure progression might be the following: the ultimate breach from uncontrolled seepage exiting at the downstream end of a containment dike adjacent to a pressurized sluice pipe results in progressive erosion, sloughing, and unraveling of the embankment soils around the sluice pipe. The erosion progresses upstream, resulting in sinkholes in the containment dike crest. Piping progresses upstream until it reaches the sluice pond and breaches the crest, resulting in an uncontrolled release of retained process water and ash. Once breached, the highly erodible soil comprising the containment dike erodes, further increasing the size of the breach, allowing rapid loss of the contents of the storage pond.
3. **The Resulting Impacts**. The method and expected magnitude of the breach or uncontrolled release is also part of the description. This would include how rapid and how large the expected release would be and the breach mechanism.

This process is illustrated in Figure 3-2.

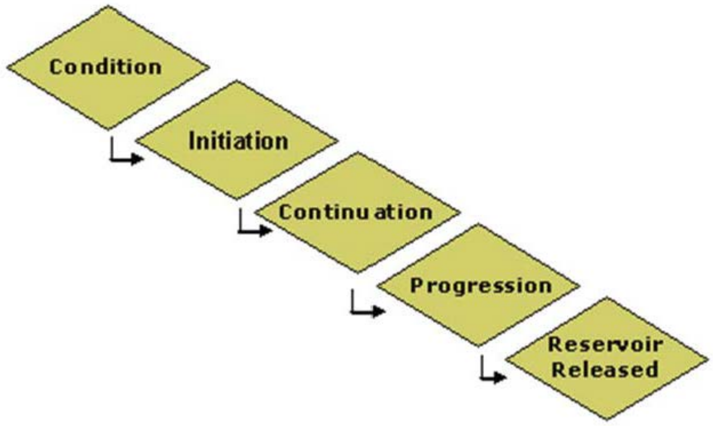

Figure 3-2
Steps in the Description of a Potential Failure Mode

The development of a sketch illustrating the PFM is often very useful in helping describe a complex failure mode. The intent for completely describing the potential failure mode is 1) to ensure that the entire team has a common understanding of the failure mode for the follow-on discussions; 2) to ensure that someone reading the PFMA report in the future has a clear understanding of what the team intended; and 3) to enable development of an event tree if the Owner chooses to perform a more in-depth quantitative risk assessment in the future. Examples of both an insufficient and a more appropriate description for a potential failure mode related to internal erosion and piping follow.

<u>Insufficient PFM Description:</u>

Piping of soil from the embankment into the foundation.

<u>More Appropriate PFM Description:</u>

When the reservoir is above elevation 5,634 feet, internal erosion of the core initiates into the open-work gravel foundation at the interface of the foundation with the cutoff trench near Station 2+35, as a result of poor foundation treatment. Core material erodes into and through the foundation and exits at the toe of the dam through an unfiltered exit. Backward erosion occurs until a "pipe" forms through the core and continues upstream until reaching the reservoir. Seepage velocities increase, enlarging the pipe until a portion of the upstream face of the embankment collapses into the pipe, which continues to enlarge until the crest of the dam collapses, resulting in an uncontrolled release of the reservoir. The process is illustrated in Figure 3-3 below.

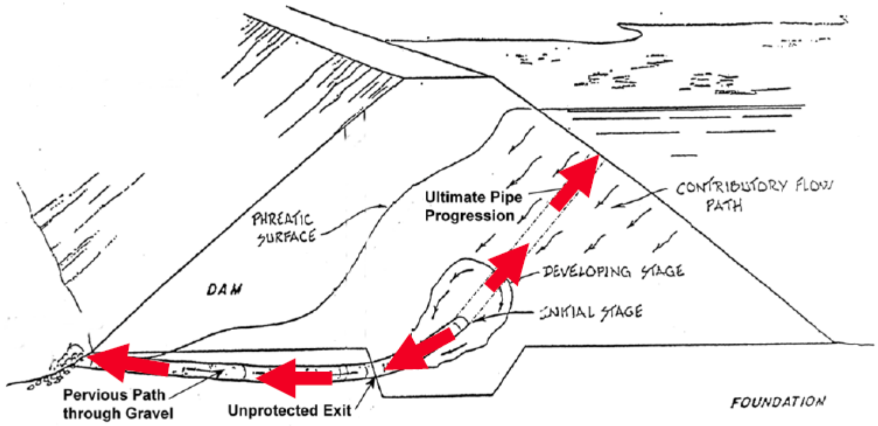

Figure 3-3
Sketch of a Potential Failure Mode

As a general rule of thumb, failure mode descriptions that combine multiple options (i.e., contain the word "or") in the description of the initiating or failure progression process should be divided into separate potential failure modes.

5d. Summarize the Adverse and Favorable Factors That Affect PFM Development

After the Team has fully described a potential failure mode, this mode is then evaluated by listing the adverse factors (factors that make a failure more likely) and favorable factors (factors that make a failure less likely) that affect the likelihood of the potential failure mode developing. These are based on the Team's understanding of the facility and background material. The Facilitator captures these in bullet form on a flip chart, which will be fleshed out later by the Independent Consultant responsible for authoring the PFMA report. These factors will have a direct bearing on the category assigned to the potential failure mode and will assist the Team during the discussion of means for inspecting or monitoring of the failure mode, opportunities for risk reduction, and possible additional analyses or investigations needed.

5e. Discuss the Consequences of Failure

The consequences of failure and the circumstances surrounding a failure (advance warning, detection possibilities, impact of the failure, etc.) should be discussed for each potential failure mode. Two major factors play a role: 1) downstream impacts of a given failure mode, and 2) how quickly the failure mode can develop, whether it can develop undetected, whether it will result in a partial or full breach of contents, and other site-specific attributes. These factors will a play a role in selecting the potential failure mode significance and the category assigned. During these discussions, the emergency action plan response to the potential failure mode scenario is examined and any concerns with the plan are discussed and documented.

Typical consequence evaluation considerations include:

- Potential for loss of life
- Downstream hazards such as bridges, power plants, commercial/industrial, residential, and institutions (schools, hospitals, etc.)
- Time for failure to develop from initiation through breach

- Ability of operator to stop failure once initiated
- Warning time
- Ability of operations staff to recognize signs of impending failure/warning signs
- Economic loss
- Environmental damage
- Clean-up

5f. Categorize the Potential Failure Modes

After a potential failure mode has been identified, described, and discussed, each potential failure mode is classified/categorized according to the classification system given in Table 3-1. Note that if team members do not reach consensus on the category, the Independent Engineering Consultant responsible for authoring the PFMA report, in consultation with the Facilitator, will make the final category selection. Dual categorization (e.g., I/II or III/II) should be avoided since there are clear distinctions between each category. The split voting should be documented in the PFMA report, noting the reasoning behind the differing opinions.

The categorization is intended to give the Owner and inspector a relative sense of the importance of each of the potential failure modes, to assist in designing the Surveillance and Monitoring Plan, and to provide focus to inspections of the CCR impoundment.

In general, potential failure modes that have been fully developed and agreed to as reasonable and credible PFMs (i.e., are a physically possible mode of failure) should be categorized as either Category I or Category II. However, there may be some potential failure modes where the physical impossibility of the failure mode is only discovered after full development of the PFM description and discussion of the likely/not likely factors. These PFMs may be assigned to Category IV.

Categories I and II are provided to allow the use of judgment by the Team and to provide an easy differentiation of relative importance for the Owner. The differentiation between Category I and II should be based on the need to "highlight" the PFM for the benefit of the Owner's operating and technical staff and for development of the Monitoring and Surveillance Plan. Generally, potential failure modes that, if activated, would result in high downstream consequences should be classified Category I. Similarly, CCR impoundments that require operation or maintenance actions to maintain adequate factors of safety (e.g., actively pumping from internal drains to reduce the phreatic surface and maintain the stability of a containment dike) should be classified as Category I to make sure that the Owner's O&M program is designed to assure that operating and technical staff are aware of the critical nature of these facilities. The magnitude of consequences is also a factor that should be used to differentiate between Categories I and II.

Category II should be reserved for those potential failure modes that are physically possible but do not need to be highlighted to the Owner for various reasons. Category II PFMs would not result in a downstream hazard; have a low probability of occurrence; or are affected by an existing monitoring or maintenance program that makes the probability of occurrence remote. For instance, failure of an interior dike where the water release would stay within the facility and not result in an off-site release could be classified Category II. Similarly, a CCR impoundment that has high calculated factors of safety, i.e., the probability of failure is remote and/or the downstream consequences are small, may also be classified as Category II.

Category III potential failure modes are those where there is insufficient information to make a determination as to classification. Generally, a Category III PFM will require additional subsurface explorations and/or analyses to determine an appropriate classification. When the additional information/analyses required to resolve a Category III PFMA are completed, that potential failure mode should be re-categorized.

Attention to monitoring and surveillance relates to Category II and III potential failure modes just as it does to Category I modes.

As noted above, in some instances a candidate potential failure mode can be dismissed as a potential failure mode without fully developing the potential failure mode. In such cases the PFM will be classified as Category IV. Category IV can also include PFMs with fully developed descriptions if the physical impossibility of the PFM is only discovered after a full discussion. The PFMA report will include a brief description of the postulated PFM and identify why the team did not discuss it in further detail. Category IV should only include PFMs that have been dismissed as physically impossible. Low consequences and/or low probability of occurrence alone are not sufficient reason to classify a potential failure mode as Category IV or IV-ND.

Note: As a general rule of thumb, seepage-related failure modes for earthen impounding structures should never be classified as Category IV or IV-ND.

5g. Identify Risk Reduction Measures

For each of the potential failure modes developed, the PFMA Team should comment and discuss possible risk reduction measures. This may involve changes in the current instrumentation and monitoring program, sluicing operations, maintenance program, or filling plan; changes to the design; or physical improvements. Typical examples include:

- Grout abandoned sluice pipes or remove as part of the closure plan.
- Confirm that observation of the outlet pipe for blockages is included in informal inspections by operations staff.
- Clear downstream slopes of vegetation so that seepage breakouts are easier to detect.
- Align monitoring frequency of instrumentation with loading rate and location.
- Evaluate and mitigate vulnerability associated with culvert blockage or other low spots along the ditch.
- Evaluate existing data focused on static and seismic liquefaction potential of the sluiced ash and any loose foundation layers.
- Perform additional analysis to evaluate stability under undrained loading.
- Consider performing a liquefaction potential analysis and seismic stability evaluation.

5h. Identify Surveillance and Monitoring Opportunities and Possible Additional Studies or Investigations

For all of the potential failure modes classified as Category I – Highlighted, Category II – Not Highlighted, or Category III – More Information Needed to Classify, the PFMA Team should comment and discuss:

- The type and frequency of current visual inspections. Do they address the identified potential failure modes? Are any changes recommended?
- Are changes to the current instrumentation and monitoring program needed?
- Is the existing instrumentation operating properly and can the readings can be relied upon?
- Are there instruments that are obsolete and serving no purpose in monitoring for the development of the Category I and II potential failure modes? Are there Category I or II potential failure modes for which additional instruments are needed?
- Are thresholds and action limits established for the existing instruments?
- Are additional subsurface investigations or studies needed to address Category III potential failure modes?

An example of a fully developed potential failure mode write-up, with likely and unlikely factors, consequence classification, recommended risk reduction measures, and possible additional investigations, is provided in Appendix B.

5i. Summarize the Major Findings and Understandings

At the end of the PFMA session, the Facilitator should ask participants to reflect on what they learned during the PFMA process and what each participant sees as the Major Findings and Understandings (MFUs) each gained during the PFMA session. Typically, this is done by going around the room multiple times until each participant has no further findings to add to the list. The items noted during the session are typically abbreviated and should accurately reflect what the individual participants stated as their major finding or understanding gained during the session.

A typical MFU write-up is contained in Appendix C.

3.6 Step 6 – Prepare the PFMA Report

The Independent Consultant prepares the draft Potential Failure Mode Analysis Report, describing each potential failure mode considered and referencing key adverse/likely and positive/not likely factors, identifying any suggested visual surveillance or instrumental monitoring, describing consequences of potential failure and site-specific conditions or factors related to consequences, and noting any potential actions identified (information inquiries, investigations, analyses or risk reduction opportunities). The failure mode should be presented pictorially whenever possible. If prepared technical presentations of new material, not contained in the record documents, were made by consultants during the course of the PFMA, their presentation should be documented in or appended to the PFMA report.

The draft report is then sent by the Independent Consultant to each participant of the PFMA session for review and comment. This outline is designed to take advantage of the information collected on flip charts during the Potential Failure Mode Analysis session in order to make the documentation process simple, fast, and effective.

All reference material available and used by the team in the Potential Failure Mode Analysis is recorded and key items of data and information that led to important findings or conclusions are included in an appendix to the PFMA report for ready reference. Sketches, photos, or graphs illustrating past or current conditions which show key information about a potential failure mode are highly recommended for inclusion in the body or appendix of the PFMA report.

The report should state whether the findings are a consensus of the team. If not a consensus, the differences of opinion and reasons therefore should be documented in the report findings. However, it is still required that the Independent Engineering Consultant make a final determination of category for all identified failure modes.

The report should include sections on additional surveillance and monitoring measures, additional risk reduction measures, and additional impoundment safety considerations discussed.

4
RAPID PFMA

4.1 Introduction

This chapter presents guidelines for conducting an abbreviated version of the full PFMA, which may be appropriate under certain circumstances. This "Rapid PFMA" approach can generally be completed in one or one and a half days. The basic elements of the full PFMA remain. However, for a Rapid PFMA the Owner will have a qualified Independent Consultant who is already familiar with the facility prepare and fully develop the PFMs (i.e., PFM description, favorable and adverse factors, consequences, etc.) in advance of the brainstorming session. In this way, the session can be devoted to a review of the prepared PFMs and a discussion of whether any of the PFMs are actually not viable and whether other PFMs have been missed and should be evaluated. The details of the process are outlined below.

4.2 The Rapid PFMA Process

4.2.1 Team Leader

The Owner identifies a staff member to lead the PFMA process as discussed in Section 2.3.1.

4.2.2 Independent Consultant

Typically, the role of the Independent Consultant and Facilitator are combined in the Rapid PFMA approach. The PFMA process works most effectively when this individual is independent of the facility owner and their staff. The IC must have extensive experience in conducting PFMAs, and should also be familiar with the analyses, design, construction, and operation of the CCR impoundment to undergo evaluation. This familiarity with the facility is important in order for the IC to do a thorough assessment of the potential failure modes specific to the facility. See Section 2.3.2 for additional requirements.

4.2.3 Identify the Core Team

The facility owner should identify the members of the Core Team who will participate in the PMFA site visit and one-day workshop. Selecting these members early will allow communication between the IC and the Core Team ahead of the workshop. See Section 2.3.2 for additional requirements for the Core Team.

4.2.4 Collect and Review Information

The IC, with the Owner's help, collects and reviews the relevant background material on the facility. The IC prepares a summary presentation that will be used to brief the participants at the beginning of the PFMA workshop.

4.2.5 Perform Site Visit

If the IC has not made a recent site visit, one should be made with the Owner's staff to update the IC on current operations, conditions, and issues. The Owner may wish to invite others who will be at the workshop to attend the site visit, if they are not familiar with the site.

4.2.6 Develop PFMs

The IC develops the PFMs, summarizes the adverse and favorable factors, reviews consequences, assigns categories, and proposes surveillance and monitoring and risk reduction measures. The steps in Section 3.5 should be followed by the IC.

The IC prepares a draft PFMA report containing the results of this preliminary PFMA for distribution to the participants in the workshop (the Core Team and others identified by the Owner). The draft PFMA report with identified PFMs should be distributed at least one week before the workshop.

4.2.7 Rapid PFMA Workshop

The IC conducts a one-day workshop after a site visit with the Core Team and other invited participants. The IC reviews background information on the facilities with the Core Team and presents the results of the PFM development. The IC facilitates a review of each of the developed failure modes. Each proposed PFM should be discussed in detail and the Core Team should vote whether to accept the PFM as presented or revise the PFM based on discussion among the team. The various adverse and favorable factors, consequences, and proposed potential failure mode categorization should also be discussed by the Core Team and revised, if necessary. The Core Team should also review and discuss the proposed surveillance and monitoring and the proposed risk reduction measures and reach concurrence.

The Core Team may decide that some presented PFMs are, in fact, not viable and/or they may decide to develop additional PFMs that are judged applicable during the workshop.

At the completion of the PFMA workshop, the participants should summarize their "Major Findings and Understandings."

4.2.8 Finalize the Rapid PFMA Report

The IC prepares a revised draft of the PFMA report for the Core Team to review. The revised draft will include updated and/or added PFMs, based on the outcome of the one-day workshop. The requirements for the report are discussed in Section 3.6. Upon receipt of comments from the Core Team, the IC will finalize the Rapid PFMA report.

5 CONCLUDING REMARKS

The purpose for conducting a PFMA for CCR impoundments is to help improve and focus the project's safety monitoring procedures and provide improvements to the safety inspection process by focusing on site-specific factors that are of greatest importance. In this way, the surveillance and monitoring program can be targeted and cost-effective, with redundant instrumentation eliminated. Recognition of the potential failure modes can inform operations and maintenance staff and inspectors who regularly observe the facility and can lead to timely intervention when early risk indicators are observed. Most failures of CCR impoundments are related to seepage-induced piping, slope instability, and foundation failures. Where possible through changes in design, operation, or physical improvements, the Owner should strive to eliminate all Category I risk exposures.

The PFMA process gathers managers, engineers, operators, and experts to identify the potential failure modes that could disrupt plant operations and impact public safety and the environment. Several recent CCR failures have led to increased public awareness, environmental concerns, and major economic loss and disruption to generating utilities' business practices. Identification of potential failure modes through the PFMA process described in this document helps increase Owner awareness and is a valuable tool in helping mitigate the risks by providing information that can improve planning, design, operation, safety inspections, and performance monitoring.

To this end, the PFMA report is a "living" document that should be revisited periodically and appended as conditions at the site change or new information is obtained at any time following the initial PFMA. The new EPA rules will require periodic inspection and structural stability assessment of CCR impoundments by an independent professional engineer once every 5 years. Prior to the 5-year inspections, representatives from the Owner's engineering and operations staff, the Independent Consulting Engineer, and the regulator (if accompanying the inspection) should review the PFMA report and discuss whether any new potential failure modes should be added or any changes in existing potential failure mode descriptions or categories made, based on site changes or new information or data that has become available. Review of the PFMA report will help focus the inspection team on site-specific factors of greatest importance.

6
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A

APPENDIX A: TYPICAL POTENTIAL FAILURE MODE ANALYSIS SESSION

Step-by-Step Description of a Typical Work Session

- Identifying key technical backup information needed
- Typical sequence of brainstorming activities
- Key information to document during the process

The intent of this appendix is to describe what is done in a typical PFMA session so participants will know what to expect and so that all the right information and data will be on hand and the people needed are there or on call.

Owner/organization prerequisite work:

Gather all background materials for review prior to the session and have them available at the session.

Required individual advanced preparation activities:

1. Core Team members have read all background materials.
2. All participants have read a general background package (inspection report and/or standards-based engineering safety report) to become familiar with or to recall the project elements and issues.
3. Inspector or instrumentation group has instrumentation and surveillance data updated and ready for review by Core Team prior to meeting and is available to demonstrate reading procedures during the site visit as appropriate.
4. Project leader has references available in meeting room. This includes:
   - All engineering reports and key feature drawings (large scale);
   - Construction photos and construction/design history data;
   - Flood frequency data and routings and earthquake loading data;
   - Data on consequences and emergency preparedness; and
   - Inspection reports and instrumentation and surveillance data.

Begin Session

I. Adequacy of Project Documentation
Discuss adequacy of documentation provided for the exercise and determine if any deficiencies exist for specific potential failure modes. Determine if sufficient

information exists to adequately perform the Potential Failure Modes Analysis for the project. Document your findings regarding adequacy or deficiencies in project documentation.

II. Potential Failure Mode Identification

A. Go loading by loading and feature by feature.

B. Have drawings or sketches of features.

Static loading (stability, seepage, rate of CCR placement):

- Go over all the key data: dike heights, dike slopes, slope protection, drainage features, available freeboard in ponds, dike penetrations, locations of spillways, etc.
- Discuss annual and historical patterns of operations.
- Discuss performance history of each feature.
- Discuss any instrumentation clues to potential failure modes.
- Discuss the relationship of geologic/foundation rock and soils to structures. Examine for potential failure modes. Determine whether or not a foundation analysis based on adequate engineering geologic studies has been completed.
- Candidate (suggested) potential failure modes are called for and means/steps to failure are discussed. A decision is made whether or not to further consider the candidate potential failure mode.
- Sketch each potential failure mode as suggested to enable brainstorming / developing / understanding. Plans and/or profiles are sometimes needed as well.
- Examine potential effects / potential failure modes / adverse conditions for impoundment structures and spillways/outlets.
- If a suggested potential failure mode is considered, the potential failure mode is clearly described.
- Evaluate failure scenarios for each significant potential failure mode. These scenarios do not have the same warning associated with flood loadings. *Note: go over each structure to see if any potential failure mode is evident.*
- Then, the reasons why the candidate potential failure mode is more or less likely to develop (adverse and positive factors) are listed on a flip chart and/or in a computer-based table.
- Based on this discussion, the team classifies the potential failure mode (Category I, highlighted; Category II, considered but not highlighted; etc.).
- Opportunities to achieve risk reduction, structural or non-structural, and ways to improve detection via instrumentation or surveillance are identified and listed.
- Data/information needs are discussed and identified.

Flood loading and impoundment overtopping:

Repeat the above process. Key changes or additions or points of emphasis in examining this loading are noted below.

- Go over all the key data: size and frequency of floods analyzed, routing data.
- Show crest elevations of key features and amount of overtopping/freeboard for each flood routed. Discuss slope protection, crest condition, discharge locations. Consider flooding on adjacent water bodies and potential effect on stability of impoundment or stack (e.g., rapid drawdown).
- Breach formation character and rate of failure are discussed. Consequences of a flood-related failure and of operational spillway discharges are discussed.
- Failure scenarios (exposure conditions and warning aspects; detection; decision to warn; dissemination of warning; evacuation, etc.) are discussed. The anticipated response is reviewed with field/site personnel. In reality, this exercise is looking for potential failure modes in the preparedness arena.

Earthquake loading

Repeat the above process. Key changes or additions or points of emphasis in examining this loading are noted below. *Note: dynamic loading follows static loading because some of the potential failure modes are similar and the degree to which the additional seismic loading may impact static condition can be examined.*

- Go over all key magnitude and frequency data for the site (historical and tectonic study data) and site attenuation or amplification data to get sense of the loading likelihood.
- Review any dynamic analyses.
- Examine what it takes for failure to occur; i.e., whether damage results in failure.
- Compare structures at the site to case histories of earthquake related failure.

Consider any other loading relevant to site:

Outlet/spillway blockages, operation, human error, etc. Repeat process used for other loadings.

III. Make Final Team Categorization

I. Significant potential failure modes (highlighted) in each loading category. Summarize/rank.
II. Potential failure modes considered but not highlighted.
III. Potential failure modes considered but lacking key data or information to allow categorization. Identify data needs.
IV. Potential failure modes ruled out.

IV. Review of Possible Risk Reduction/Instrumentation/Surveillance Opportunities Identified for All Potential Failure Modes Considered

Place the identified potential risk reduction opportunities into two categories:

1. Possible alternative mitigation actions to investigate, and

2. Actions to be considered by the Independent Engineering Consultant for implementation by the Owner.

V. Identify and Record Major Findings and Understandings

The Major Findings and Understandings achieved as a result of the session (give team members a few minutes to think about these before listing) along with the description of each potential failure mode considered should be written up and distributed to participants of the PFMA session.

VI. Documentation of PFMA Session

The Major Findings and Understandings achieved during the session and the PFMA report should be documented as discussed in Section 3.6 – Step 6.

B

APPENDIX B: EXAMPLE POTENTIAL FAILURE MODE WRITE-UP

Given below is an example write-up of one potential failure mode from a PFMA session for a fossil plant consisting of an active ash disposal area (complex).

CCR Ash Complex

Potential Failure Mode 12: Global stability failure of exterior slopes of the CCR complex in undrained, steady-state conditions.

PFM Description: Raising of the active ash stack results in undrained loading conditions within either the loose, saturated ash and/or the weak foundation alluvium, resulting in slope instability, failure, and loss of containment.

PFM Category: I

Likely/Adverse	Not Likely/Positive
Material is highly variable. Cone Penetrometer Test (CPT) results could be interpreted to reflect lower strengths. Test/drilling locations are on the stack perimeter – material strengths have to be location-biased since this is where most of the equipment passage has been located. History of seepage breakouts on the slope – confirms high phreatic conditions within stack. Need to assure that operations are planned to minimize negative impacts on stability. No internal drainage.	Comprehensive subsurface investigations have been performed. Computed Factor of Safety (FS) slope stability exceeds 1.5; these analyses reflect addition of buttresses. Design soil parameters are based on conservative selection from available laboratory test data results. Material strength of sediments within the interior of the stack is less critical to sliding stability compared to that under the exterior slopes. No new stacking planned after closure (planned 2025). No history of global (deep) sliding during operational history. Monitoring includes piezometers, limited slope inclinometers, and visual inspections. Trigger levels are in place for piezometers to maintain adequate stability – based on historical levels. Buttresses added to enhance stability. Stability analysis assumes conservative piezometric levels.

Rationale for Selected Category: Additional stacking is planned as late as 2025. The material is highly variable in nature. Category I classification was selected to highlight the need to assure future stacking operations are planned to minimize overall risk to stability.

Potential Risk Reduction Measures:

- Provide clear direction and formal documentation for alignment between design and analysis assumptions and operations
- Continue current monitoring of piezometers and inclinometers
- Determine if additional parametric studies are needed
- Operations (stacking) and closure plans should reflect the PFM discussion
- Update/confirm stability analysis and STID

Surveillance and Monitoring Enhancements:

- Install additional slope inclinometer, including continuous arrays
- Install vibrating wire piezometers (low volume)
- Install settlement monitors (Sondex or equal)

C

APPENDIX C: EXAMPLE MAJOR FINDINGS AND UNDERSTANDINGS WRITE-UP

Given below is an example write-up of the Major Findings and Understandings gained from a Potential Failure Mode Analysis for a fossil plant consisting of an active ash disposal area (complex).

General MFUs

1. A site-specific liquefaction potential analysis has not yet been performed for any of the stacks at the XYZ Plant. The XYZ site is located in an area of moderate seismic activity, and the controlling seismic source zone is Zone 5 with an MCE (Maximum Credible Earthquake) M = 5.8.
2. During a potential failure mode at the reservoir (elev. XXX ft.) extreme high water will occur on all sides of the ash stack, dredge cell, and stack complex. Though these facilities may be active or in closure when/if this should occur, rapid drawdown conditions due to reservoir operations could cause management containment problems and significant environmental damage around the site.
3. An earthquake of magnitude M = 5.0 is possible and historically valid and could occur in the free field (randomly) at the site with frequency content that could be of concern for response of the structures.
4. The stormwater management plans for all active/inactive/closed CCP facilities should include design features that adequately address the potential overtopping of perimeter dikes. This is especially true for multiple-cell facilities and ponds-in-series.
5. In the past several years, at least four stormwater management/seepage-related failures have occurred in the December-January timeframe.
6. A number of potential failure modes were related to daily operations in managing both sluice water and stormwater. These operations issues need to be clearly understood for the remaining life of wet operations on the stack.
7. Seismic analysis must be completed soon as a part of the closure plan. There may be additional failure scenarios that develop out of the seismic analysis.
8. The static liquefaction issues need to clarified/resolved.
9. Multiple incidents involving instability or erosion, some involving slope failures, have occurred at the stack complex in the past. Progressive instability of surrounding materials has not been reported during these incidents.

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